Abstract—High temperature superconducting (HTS) machines are recognized to offer several advantageous features when comparing to conventional ones. Amongst these, highlights the decrease in weight and volume of the machines, due to increased current density in conductors or the absence of iron slots’ teeth; or the decrease in AC losses and consequent higher efficiency of the machines, even accounting for cryogenics. These concepts have been already demonstrated and some machines have even achieved commercial stage. In this paper, several alternative approaches are applied to electrical motors employing HTS materials. The first one is an all superconducting linear motor, where copper conductors and permanent magnets are replaced by Bi-2223 windings and trapped flux magnets, taking advantage of stable levitation due to flux pinning, higher current densities and higher excitation field. The second is an induction disk motor with Bi-2223 armature, where iron, ironless and hybrid approaches are compared. Finally, an innovative command strategy, consisting of an electronically variable pole pairs’ number approach, is applied to a superconducting hysteresis disk motor. All these concepts are being investigated and simulation and experimental results are presented.

Index Terms—High-temperature superconductors, hysteresis motors, induction motors, superconducting rotating machines, synchronous motors.

I. INTRODUCTION

The reason underlying the application of high temperature superconducting (HTS) materials in electrical machines is related with electrical and magnetic features that makes them attractive when comparing to conventional conductors and permanent magnets. Amongst these highlights the ability to carry high current densities (up to $10^5$ MA/m$^2$ at 77 K and 5 T for second generation conductors [1]) and to consequently generate high flux densities in the surrounding medium. This allows in some cases for iron removal, either completely or slots’ teeth, leading to lighter and compact machines, or to decrease in AC losses, improving efficiency, although cryogenics must be taken into account.

Several HTS electrical machines have been built in the past as, e.g., homopolar [2], [3] or synchronous machines [4]–[7], or fractional horsepower motors such as reluctance [8], [9] or hysteresis motors [10], [11]. Other concepts have been applied, as trapped-flux motors, see e.g. [12], [13], where superconducting bulks are used as permanent magnets. HTS application in linear motors is also motivated by the aspect of stable levitation associated with these materials. As with rotating motors, they are usually present in the armature [14] or in the excitation system [15].

One of the most relevant HTS machines applications are the megawatt range synchronous machines, which has also achieved commercial stage. A comparison of HTS and conventional HTS machines efficiency is shown in Fig. 1, where it is clear that this is not the most important driving parameter. In fact, the decrease in weight and volume reported by American Superconductor company is to less than half of the dimensions of a conventional machine with only 60% of rated power [7]. Nevertheless, fractional horsepower machines, as the ones described in this paper, are important in applications where cryogenics is already present.

This paper focuses on the design and implementation of the latter machines, and new approaches are foreseen. In the next section an all superconducting linear synchronous motor is presented. The term all HTS concerns both with the absence of iron and with the presence of HTS armature and excitation. An induction axial flux disk motor is then described, and several approaches compared. Finally, a hysteresis disk motor, with control system based on magnetic poles electronic variation is presented. Along the paper, theoretical, numerical, simulation and
II. All Superconducting Linear Synchronous Motor

The first motor described in this paper is an all superconducting linear synchronous motor. The term “all superconducting” is related with the fact that, besides being an ironless motor, the device is built by HTS armature and excitation.

A. Motor’s Topology

1) Armature: The motor’s armature is built by Bi-2223 20 turns windings in a three-phase double stator configuration, see Fig. 2, fed by a current inverter. This is intended to generate high flux densities in the surrounding medium, in order to eliminate iron, thus implementing a light device. The first approach, described elsewhere [17], [18], is built by a single stator’s topology, which lead to strong magnetic flux density components perpendicular to the tape surface, thus severely degrading its superconducting performance; and to the development of vertical and thrust forces of comparable amplitude, thus degrading its mechanic and control performance. The double stator’s topology, as shown later, eliminates those restrictions.

2) Excitation System: The excitation system, placed on the mover, consists of two YBCO bulks pre-magnetized in opposite directions, thus implementing two magnetic poles, see Fig. 3. The trapped flux magnets are intended to trap flux densities higher than conventional permanent magnets, also contributing to a higher specific power of the machine.

B. Experimental Results

1) Armature: In order to simulate a particular configuration of the armature’s currents, the armature phases A, B and C are supplied with the following currents: phase A with 65 A, phase B with 0 A (in fact, its windings are not present), and phase C with –65 A. The flux density field is then measured along the armature, on a plane in the middle of both stators, using a transversal Hall probe. The resulting field is plotted in Fig. 4, along with simulated results, which are in accordance. Simulations are performed with the finite elements software Flux2D, from Cedrat company.

2) Excitation System: In order to estimate the critical current of the YBCO bulks, a pulsed field magnetization system was used. A one second 1000 A pulse was applied using four current sources in parallel, each with a maximum capacity of 400 A. The system is depicted in Fig. 5. Two magnetizing copper coils are used, each built by 10 stacked coils of 10 turns each, thus achieving 100 kA · turn. The resistance of the coils is 2 mΩ at 77 K, leading to a voltage drop of about 4 V, which is adequate to the sources (maximum 15 V). Experiments made before cooling the system showed a rough relation of 1 mT/A in the middle of the coils, thus leading to a magnetizing field of nearly 1 T.

After magnetizing the bulks, the trapped flux profile was mapped with an axial Hall probe, confirming the presence of two domains (as mentioned by the manufacturer), one of which was damaged. This is confirmed by the three peaks in the profile.

In order to use the sand-pile model [20] to estimate the critical current of the bulk, a simple approach was made, considering it as a single domain. A critical current density of 52.508 A/cm² is obtained by fitting. The experimental and modeled profiles are plotted in Fig. 6.

C. Numerical Determination of the Developed Forces

Data from measurements were used to numerically determine the thrust and vertical developed forces, according to the methodology previously proposed in [17]. The forces are plotted in Fig. 7, and with the current topology, no vertical forces are developed, leading to a better performance when comparing with the single stator topology [17], [18]. The position of the mover...
where thrust is maximized is numerically found as $[38^\circ; 98^\circ]$, i.e., $x \in [0.21\pi; 0.54\pi]$.

### III. Induction Axial Flux Disk Motor With HTS Armature

This double stator motor is built by 12 Bi-2223 armature coils, similar to the previously described, see Fig. 8, with an average coil’s critical current of 88 A. The rotor consists of an aluminum disk assembled on a stainless steel shaft, with dimensions optimized according to [21].

#### A.

The configuration of the coils leads to high harmonic distortion, where harmonic components are not negligible. Each harmonic’s individual effect is calculated and summed to give total developed torque. The $k$-th torque component is calculated as [22]

$$T_k(\Omega) = r_{avg} \cdot \pi \cdot J_s^2 b_k^2 \cdot \frac{k \cdot e \cdot (\omega_1 - \Omega) \cdot k}{\rho \cdot \mu} \left(1 + \frac{\omega_1 - \Omega}{\omega_1 - \Omega} \cdot k^2\right)$$

where $r_{avg}$ is the rotor radius and $e$ its thickness, $J_s$ the current density amplitude of the coils, $b_k$ the $k$-th harmonic Fourier coefficient, $\omega_1$ the angular velocity of the rotating field, $g$ the airgap, $\rho_{vol}$ the volume resistivity and $\Omega$ the angular speed of the rotor. The torque developed by each harmonic is qualitatively plotted in Fig. 9. The greater the harmonic order, the smaller is its corresponding synchronous speed, $\omega_{sk}$, given by $\omega_{sk} = \omega_1/k$. As can be seen in Fig. 9, for the $k$-th harmonic, when the speed of the rotor is higher than the corresponding $\omega_{sk}$, the developed torque is negative, resulting in a brake effect. That affects the total torque, $T_T$, also plotted in Fig. 9, leading to a motor’s behavior as a motor ($T_T > 0$) or as a brake ($T_T < 0$), depending on the slip.

#### B. Simulations

Disk motor linearized version simulations were performed with Flux2D in order to compare the performance of different topologies, namely toothless iron, ironless and hybrid (iron and teeth) topologies, called $T_1$, $T_2$ and $T_3$, respectively. Results are plotted in Fig. 10, and, since saturation of iron is never achieved, iron topologies are clearly better, as expected.

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Fig. 6. Trapped flux profile in one YBCO bulk. The modeled field is obtained by profile’s fitting using sand-pile model. $J_c$ is found to be 52.508 MA/cm².

Fig. 7. Numerically determined developed forces. As a consequence of the double stator topology, no vertical forces are developed.

Fig. 8. Half stator of the induction motor.

Fig. 9. Qualitative results of the torque developed by 1st, 3rd, 5th, and 7th harmonics, for 50 Hz supply frequency. Total developed torque is also shown.

Fig. 10. Qualitative results of the torque developed by topologies $T_1$, $T_2$, and $T_3$, for 50 Hz supply frequency.
C. Experimental Results

Prototypes for topologies $T_1$ and $T_2$ were built, see Fig. 11. The motors were tested at 77 K, 5 V and 63 A (rms values). A powder brake was used to obtain torque/speed characteristics. The curve for $T_1$ is plotted in Fig. 12. For topology $T_2$, the developed torque was insufficient to overcome static and dynamic friction torques. This reinforces the idea that there is no advantage, in this motor’s configuration, to remove iron. The slip is also very high (>80%), confirming theoretical and simulation results, although the important contribution of bearing losses was neglected in these analyses.

IV. AXIAL FLUX DISK MOTOR WITH ADVANCED CONTROL SYSTEM

This motor is built by two half stators with 24 slots and 24 independent conventional copper windings each, see Fig. 13, a rotor made by an aluminum or YBCO disk, and a screw system that allows adjusting the airgap.

The motor’s behavior depends naturally on the rotor’s material, being an induction (aluminum rotor) or a hysteresis motor (YBCO rotor). The latter presents two operating regions, synchronous and asynchronous, depending on the load and pinning properties. In asynchronous mode, flux flow regime dominates.

A. Control Strategy

With the use of power converters, independent supply phases may be generated [23], which, together with an appropriate armature design [24], allows designing versatile control systems, as exemplified in [25]. Maximum operation in torque/speed space is achieved if frequency variation is associated with changing the number of magnetic poles of the motors, as described in [26].

For a given pole configuration, the motor speed can be modified by a simultaneous action on frequency and input voltage (V/f control). On the other hand, the torque/speed characteristic is modified by changing the number of poles. A higher number of poles leads to a lower synchronous speed and higher torque, and vice-versa. This is similar to a mechanical gearbox operation, although in the present case this is implemented electronically.

B. Simulation Results

A linearized version of the motor was simulated using Flux2D. The synchronism speed of a linear motor, $\nu_s$, is given by

$$\nu_s = 2\tau \cdot f / p$$

where $\tau$ is the pole pitch considering one pair of poles, $f$ is the frequency of the supply voltages, and $p$ the number of magnetic poles pairs. Considering $f = 50$ Hz and $\tau = 0.006$ m, the synchronism speed is 4.8 and 3.2 m/s for two and three poles pairs, respectively. Simulations were performed considering the two rotor materials, aluminum and YBCO, and results are plotted in...
Fig. 14. As mentioned, the latter configuration presents a synchronous behavior, as simulations were considered, in both rotors, for no load conditions.

The mentioned gearbox operation was also simulated and the results are plotted in Fig. 15, where dynamic torque and speed are shown when the number of poles is changed.

V. CONCLUSIONS

In this paper, three different approaches were presented in fractional power HTS motors design and control. The first approach was an all HTS motor, while the second was an induction axial flux disk motor with an HTS armature and the third a HTS hysteresis (or conventional induction) axial flux disk motor with an advanced control system. Numerical, theoretical, simulation and experimental results were presented, allowing clarifying the challenges and consequences of using HTS materials to build the armatures of these motors, excitation systems or rotors.

REFERENCES